SleeveAR: Augmented Reality for Rehabilitation Using Realtime Feedback

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Dissertation for the Degree of Master of
Engineering Systems and Computer Engineering

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October 2015

Acknowledgements

I would like to thank my canary. Ana Paula Morais Cabral fisioterapeuta

Lisboa, October 2015

João Tiago Proença Félix Vieira

For blablablablabla,

Resumo

My abstract in Portuguese.

Abstract

After being exempted from in-clinic physical therapy, it is usual for a patient to continue performing exercises outside of the clinic and without any therapist's supervision. While performing unsupervised exercises, it would be desirable to receive similar feedback as the one provided by a physical therapist, to maintain a certain quality in the task execution. To address this problem, several approaches using feedback for rehabilitation have been implemented. Unfortunately, the test subjects frequently reported difficulty in completely understanding the feedback given to them, therefore failing to correctly execute the given movement.

Palavras Chave
Keywords

Palavras Chave

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Keywords

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Acronyms

AR Augmented Reality

PT Physical Therapist

RS Rehabilitation System

KP Knowledge of Performance

KR Knowledge of Results

MFM Multimodal Feedback Manager

DTW Dynamic Time Warping

1 Introduction

Summary

1.1 Problem

Even though physical therapy holds a great part of a injured person's rehabilitation, it also requires effort from the patient to achieve a full recovery. In fact, the patient holds great responsibility in each therapy session. He must be ready to learn about his condition and what types of therapeutic exercises to do and how to perform them whenever not being supervised by a therapist (e.g., whenever performing exercises at home). To be able to exercise alone, a patient must be taught about his body and body movements, i.e., he must gain *body awareness*.

A person with an acceptable body awareness has a better knowledge of his body and how to correctly move it when doing exercises or other tasks that involve physical movement. Therefore, a person is able to improve the overall quality of a given movement and to diminish unnecessary muscle tension, by being able to use just the muscles required to accomplish a given task (2). With relatively low body awareness, it becomes hard for a patient to perform well alone and may end up hurting himself. Consequently, to help people with low awareness execute *prescribed* tasks, it is necessary for them to receive real-time feedback. This feedback is usually given by a professional, but without their presence, it would be desirable for people to receive similar feedback from other sources, in order to maintain a certain quality in the task execution.

Augmented Reality (AR) is a technique used to impose digital content on top of the physical world, giving the user a different perception on the subject in which AR is being applied. This can manipulate the meaning or increase the amount of information available of the subject being augmented.

AR could be a possible solution to overpass the lack of clear feedback sources when no Physical Therapist (PT) is present. It holds great potential in the field of rehabilitation and there are already a variety of tools available to help with the development process of Augmented Reality applications that interact with the body(3).

If combined with a carefully designed form of feedback for the patient, AR can be of great use in the rehabilitation of a person (4). The whole idea of it is to give more information to a person in a way that it can make the assigned task easier to do. Therefore, the type of feedback given by the AR system can have a great influence on the outcome of the task being done.(5)

As above mentioned, the feedback given to a patient helps him to correct mistakes on the performed movements. Usually, this feedback is given by a therapist while enduring physical therapy, which can be of a visual form (the therapist demonstrating what to do), auditory form (the therapist giving orders to the patient) or physical (the therapist applying physical force to the patient). When performing exercises alone, a different approach must be followed on the types of feedback used, making sure that the goals are still achieved and the patient performs the exercises correctly.

There are multiple types of feedback, just as there are forms of expression, which means that there could be different combinations of feedback that could make a patient understand the task better. Most of the traditional feedback systems, used for rehabilitation, only use a singular type of feedback, visual or auditory(6), being these kind of systems known as *unimodal feedback systems*.

By using multiple types of feedback, we can take advantage of more than one sense on the patient, making it possible to give more information without overloading just one sense (e.g., just using visual cues on a screen can become overwhelming for a patient). A system like the one described is called a *multimodal feedback system*, which, by definition, uses various sensory inputs and outputs to achieve the desired task.

1.2 Goals

With this work we want to explore the possible benefits of using augmented reality with multimodal feedback for guidance in a rehabilitation context.

We plan to analyze several solutions in a variety of fields that rely on feedback for user interaction. With this analysis we intend to detect the flaws in the current solutions being presented for interaction and evaluate which approaches, if combined, could have a chance of improving the guidance methods being used with patients.

The document structure is as follows: first, in section 2 we will explain all the required concepts that are connected to this work and overview the state of the art in home rehabilitation systems, giving priority to the ones which use some kind of virtual or augmented reality interaction. Also, and most importantly, the feedback strategies used, not only in these approaches but also in other examples, will be analyzed and compared. At the end of this section, an overview will be presented with some conclusions about the current state of the art in multimodal feedback.

Further in the end, in section , we will describe our approach with detail, explaining our goals while presenting the planned system architecture and evaluation methods to be used.

1.3 Approach

1.4 Contributions

Studies have already shown that the use of augmented reality feedback enhances the motor learning of an individual (4). Aiming to a home rehabilitation process without the presence of a therapist, the feedback has the responsibility of guiding the patient and correcting him throughout his tasks.

By experimenting on the several forms of feedback that can be used on a patient, we want to evaluate which combinations can be useful to specific tasks and how can they complement each other in a way that it creates a clear a clear set of instructions for the patient. In the end, we want to be able to determine the most appropriate feedback combinations to successfully guide a person through a given movement. Hence, the aim is to contribute to future augmented reality feedback applications that might need to interact with a user in the clearest possible way.

1.5 Publications

{TODO: rehab workshop?}

1.6 Document Organization

2 Related Work

Summary

Motor rehabilitation, or motor re-learning, is an extensive and demanding process for a patient. For a successful recovery, the patient must be disciplined and understand that this is a tough and painful task in which it will normally be required to move the injured area which might cause immense pain(2). Depending on the injury, it requires several physical therapy sessions and, after finishing them, the rehabilitation might have to continue at the patient's own home(7).

Home rehabilitation is common among injured individuals, since attending sessions at a professional clinic is usually not enough for a full recovery. The patient will need to add more effort outside of the clinic and continue exercising to avoid suffering a setback on his rehabilitation (8) or to increase his recovery speed. This requires him to learn what exercises to do and how to do them correctly to prevent an aggravation of the injury(9).

There is a significant difference between rehabilitation with a PT and without him. When a patient is attending physical therapy, it is the therapist job to help him fight his pain and recover from his injury. His role is fundamental to plan what exercises the patient must do and to make sure they are executed correctly. Since the patient does not always has the ability to execute alone the exercises, or not even move without an external help, the therapist can intervene during the session and adapt his approach according to the patient's needs(4). However, whenever the rehabilitation exercises are done at home, without the therapist presence, the patient might perform incorrect movements to avoid pain(9) or might not even be able to move at all.

Repeating specific movements is a key factor in motor re-learning (10) and it will always be a part of the rehabilitation, whether at a clinic or at home. This is one of the main causes of deteriorated rehabilitation at home. In this case, patients tend to get bored and lose focus, due to this repetition and lack of a therapist presence to guide and motivate him (2; 11; 12). To help with this unsupervised rehabilitation work, several solutions have appeared as an alternative to the classic paper or video instructions.

Using modern technologies and counting on an increasing offer in affordable tracking devices (e.g. Microsoft Kinect), a large diversity of applications are being developed that aim to solve some of the difficulties in unsupervised rehabilitation (13; 8). Several such works, focused on rehabilitation, will be discussed in the next section.

2.1 Rehabilitation Systems

Nowadays, we can observe a wide variety of rehabilitation systems which can help improve the recovery of a patient. Many of them have different rehabilitation goals and focus on specific injuries, e.g., stroke(8; 6), or limbs rehabilitation (14; 15; 16).

The use of these systems can have a great influence in a patient's rehabilitation outside of a clinic. Not only it allows to maintain a certain quality on the execution of exercises, but also enables the patient to exercise in a comfortable environment, his home, which makes it easier to stimulate and motivate him during the whole process (8).

As it has been said previously, a patient's rehabilitation is related to three concepts: repetition, feedback and motivation (10). Hence, the development of a Rehabilitation System (RS) should always be influenced by these three ideas and how to approach them.

The repetitive nature of rehabilitation exercises can quickly become boring for a patient(12; 15; 17), therefore, there is a need of turning these exercises into something less tedious. It is believed that when dealing with repetitive exercises, the main goal should be divided into several sub-goals. This way the patient keeps achieving incremental success through each repetition and increases his motivation when comparing to the approach where success is only achieved after finishing the whole task (10).

For a patient to be informed about his execution, the feedback provided can be given in two different ways. During the execution (concurrent feedback) or at the end (terminal feedback)(4). The concurrent feedback is given in real-time with the purpose of offering correction or guidance, it allows the patient to have Knowledge of Performance (KP). On the other hand, terminal feedback only allows the patient to know if he succeeded after fully executing the task, giving him Knowledge of Results (KR) (6; **?**).

Studies have shown a difficulty in obtaining a flawless formula when it comes to relating KP and KR. On one hand, KP helps to accelerate the learning process of the exercise by correcting the patient in real-time. On the other hand, prolonged KP can create a dependency on the feedback, interfering with the learning process. Therefore, Sigrist (4) states that KP should be reduced as the exercise keeps advancing, gradually giving more emphasis to KR in order to stimulate the autonomy of the patient.

Gama et al. (3) developed a rehabilitation system in which the user position was tracked using a Microsoft Kinect. In this system, the user would see himself on the screen with overlaying targets that represented the desired position. If a incorrect posture was detected (shoulders not aligned or arm not fully stretched) he would be notified in real-time with visual messages. White arrows on the screen were also used as visual cues to guide the patient's arm to the target. For each repetition, points were added to a score, depending on how well the user performed.

Another work (16) focused on rehabilitating stroke victims which normally end up with one of the arms extremely debilitated. In this case, the main focus was to motivate the patient to move his injured arm. Even with a small range of motion, it is important for the patient to move it in order to improve the recovery. The patient would see a virtual arm overlaying his injured arm, which would simulate a normal arm movement. The virtual arm position was calculated based on a few control points around the patients shoulder and face. The results shown an enhancement of the shoulder range of motion in all the test subjects.

Also focused on stroke victims, Sadihov (14) proposed a system which intended to aid in the development of rehabilitation exercises with an immersive virtual environment. In this case, using a haptic glove with vibration capabilities. Three virtual games were developed where the user could interact with his hand. The vibrating motors on the glove were activated according to what happened in the game. For example, in one of the games, the user had to hit the incoming meteors with his hands to protect a village and every time one meteor collided with the avatar's hand, the haptic glove would also vibrate. This enabled patients to feel more connected with the game and thus become more motivated to exercise their debilitated limb.

Due to improving motivation and diminishing boredom while rehabilitating, using serious games has been a trend in the latest years as we can see for the several research published around the theme (18; **?**; **?**; **?**; **?**).

Tang et al. (9) developed Physio@Home, a guidance system to help patients execute movements by following guidelines. The patient would see himself on a mirror and, on top of the reflection, visual cues that indicated the direction to which the arm should move. The exercises were pre-recorded by another person and then replicated by the patient.

Most approaches usually rely on Augmented Reality technology, enhancing our perception of the real world by adding information or manipulating our surroundings.

2.2 Augmented Reality

Nowadays, Augmented Reality applications are being developed for several fields such as entertainment, games, military training and medical procedures (19; **?**). It is rather hard to list all the possibilities of augmented reality when its limit can only be imposed by one's creativity (if we ignore technological limits). Its use can, for example, allow a surgeon to monitor a patient's heartbeat and temperature in real time, or even help a military jet pilot to see targets info in his visor while flying.

In the rehabilitation field, AR has been increasingly the target of research works. The possibility of creating interactive and immersive environments allowed to solve some of the difficulties of classic rehabilitation.

For example, a PT could have a better judgment over a patient's condition if he had access to the patient's real time data regarding body posture, joints angles or movements in general, thus helping him to better evaluate the patient's condition. Without augmented information, this type of information could only be obtained through naked eye estimates or by using regular video recordings.

A common approach in this field is to use augmented reality mirrors. This is inspired by the need for a patient to be able to see his body while learning and executing movements, mainly to help with spatial awareness. We can often see mirrors placed in physical therapy clinics for this reason and, therefore, augmented reality mirrors can be considered an "evolution" of the classic mirror. But not only in rehabilitation can AR mirrors be useful: we can observe the presence of mirrors in any activity that requires movement learning, like dancing or martial arts.

Next, we present some examples where augmented reality mirrors were used.

2.2.1 Augmented Reality Mirrors

Mirrors allow a person to have visual feedback of his body. It enhances the spatial awareness which is useful for motor learning activities.

The concept of an AR mirror does not necessarily require an actual physical mirror to be implemented. Its functionality can be easily simulated by a virtual mirror which consists in capturing images with a camera and projecting them in real-time on a screen facing the user, giving him the perception of a real mirror.

Nevertheless, there has been implementations of AR in actual physical mirrors (20). This was achieved by creating a mirror with a partially reflective layer facing the user and a diffuse layer in the back. The reflective layer maintained a mirror natural reflection while a light-projector projected images onto the diffuse layer. The result was a mixture of the user's reflection with virtual images.

Virtual mirrors could be considered an easier alternative to implement than the one used above. By allowing any screen to turn into a mirror with the use of a color camera, it is normal that this seems to be the most common approach.

AR makes it possible to add more capabilities to the classic mirror. In a visual feedback perspective, we can generate virtual images on top of the reflection (for instance, for guiding purposes). There has been already applications that make use of AR mirrors to guide a user, whether it be for rehabilitation (9; **?**; **?**) or for other types of interaction not focused on rehabilitation (21; **?**).

Although AR mirrors have proven to be useful for visual feedback, there are some limitations. An obvious limitation of this virtual alternative is the "reflection" dependency on the camera direction, so that if a user looks at the screen from a different direction other than directly forward, the reflection would not be correct. The lack of depth perception means that 3-dimensional movements are more difficult to be guided by virtual images on a flat screen. We can conclude that AR mirrors are more suitable for 2-dimensional movements. One possible way of solving this limitation, is to combine other augmented reality sources in a way that they can complement each other and not be stuck within a screen.

2.2.2 Augmented Reality with Light-Projectors

Using light-projectors for augmented reality has enabled the creation of very interesting applications. Through techniques of projection mapping, it became possible to turn any irregular surface into a projection screen. We can observe this technique being applied in different objects. It is regularly used for live shows using buildings as the screen. One example could be the promotion of the movie "The Tourist" where projection mapping was applied to an entire building (22). But it can also be used on the human body to obtain interesting effects. Barbosa (23) used projection mapping to shoot a music video in just one take where mesmerizing effects were applied onto the singer just by using a projector. By using projection mapping we can alter an object perception and create optic illusions.

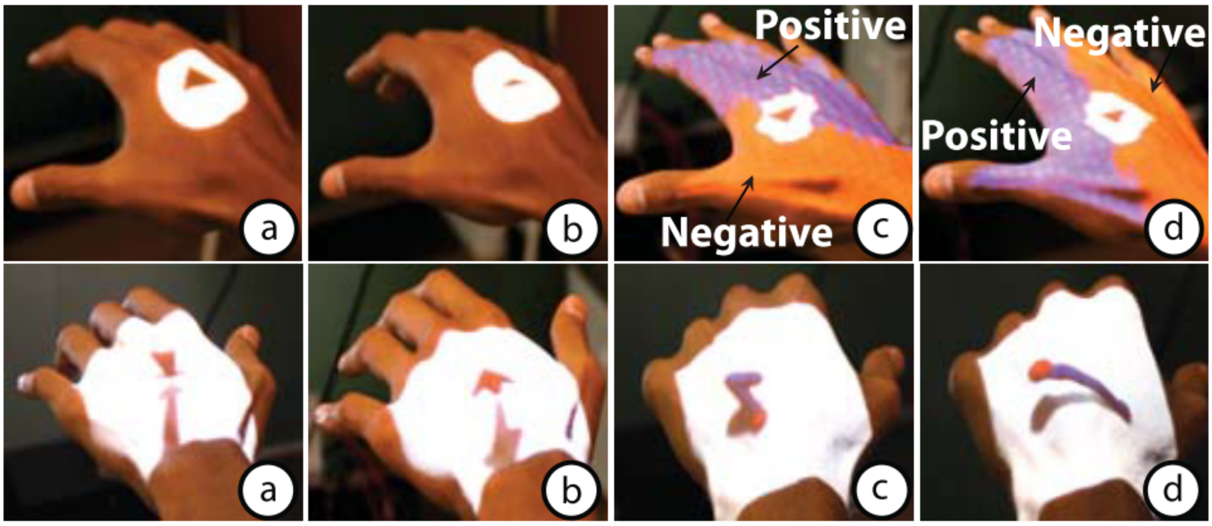
This kind of technique can bring great benefits to fields that rely on guiding feedback by being able to focus projection on a body part for example, just as it is necessary in rehabilitation systems. But for it to be useful, the projection mapping should be interactive and done in run-time instead of being pre-recorded like the examples above.

LightGuide (1), explored the use of projection mapping in a innovative way. The projection was made onto the user, using his body as a projection screen. Real-time visual cues were projected onto the user's hand in order to guide him through the desired movement. By projecting the information in the body part being moved, the user could keep a high level of concentration without being distracted by external factors. As we can in the examples shown in Fig. **??**, different types of visual cues were developed, having in mind movements that demanded degrees of freedom over 3 dimensions. For each dimension a different design was planned so that the user could understand clearly to what direction should his hand move.

To apply real-time projection mapping onto a moving body part, its position must be known at all time to make sure the light projector is illuminating the correct position. For this, motion tracking devices are used which enable to record the movement of, in this case, a person.

2.3 Tracking Techniques

Tracking devices have enabled the development of more immersive interactive applications. Whether it be for entertainment or more serious matters, the possibility of interacting with an



interface without using any kind of handheld devices can greatly enhance a user experience.

Nowadays it is possible to obtain affordable tracking devices such as Microsoft's Kinect, which can provide full skeleton tracking without the use of any kind of special equipment. As opposed to more professional solutions that require special suits with markers, but provide a more accurate tracking. Even so, studies have shown that Kinect has an acceptable accuracy in comparison with other motion tracking alternatives and can be considered a valuable option for its low price and easy portability (24; 25).

To provide interactive content, the user's body must be detected and its position passed as input. This input normally consists of several tracking points which represent body joints. Their relative position between one another give us a representation of the user's current body posture, since each connection between two joints can be considered a bone as we can see in the Fig. 2.1. In the Kinect's case, being a markerless tracking device, these joints are defined through software.

Aiming at rehabilitation, using tracking technology could enable applications to track a therapist's demonstration of a given movement prescribed to a patient. Then, when the patient performed it, his movement could also be tracked and compared to the therapist's demonstration to detect possible errors. For this to be possible, several factors have to be taken into account like the possible physical differences between both. If we were to make a "blind" comparison between both skeletons, the results would not be accurate.

Two comparison methods that can be used to address the aforementioned problem are described hereafter.

2.3.1 Skeleton Comparison Methods

In order to facilitate the description of the following methods, we will consider two given skeletons named SK1 and SK2, both with the same number of defined joints and where SK2 wants to mimic SK1's pose.

The first method of measuring differences between skeletons is through the usage of their joints position. As we can see in Fig.2.2, SK1 and SK2's arms are not in identical positions. If we consider the euclidean distance between joints J11 and J12, they might never be considered equal if their arms have different lengths. If the euclidean distance never reaches zero, these two joints might never overlap. As we can see in Fig. 2.3, when both skeletons achieve identical pose, there still exist a distance A between them, therefore by using the joint position this would not be an identical pose between them. To solve this problem, another method must be used for comparison, which relies on other measurements not dependent of, i.e. invariant to, joint specific position.

If we use the joint angles for comparison, it is possible to achieve better results due to the physical differences not influencing the measurements (8). In this case, looking once more at Fig. 2.3, if we take into account the joint angle B, both skeletons can be considered to have an identical posture, even though they have different arms length.

The accuracy of skeleton comparison has a important role in rehabilitation systems where the patient will be corrected in real-time. His body tracking data will be the base of the system behaviour and it will influence how it responds to the patient. Next, we will analyse the state of art concerning several different approaches for the provisioning of feedback information to the patient.

2.4 Information Feedback

The basic goal of feedback is, as the name says, to feed information back to the user. It does not have to be in a textual form even though that is the most common form of feedback used for humans. We can receive information by using different means of communication. Everyday

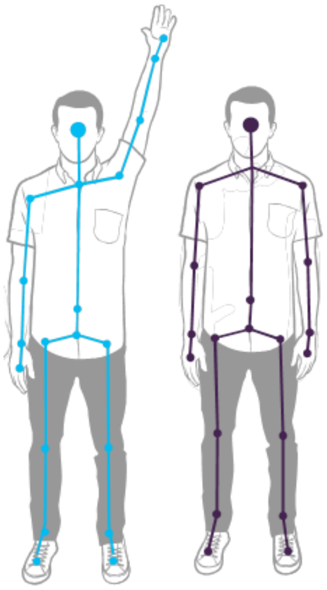


Figure 2.1: Joints position from Kinect

Figure 2.2: SK1 shows desired pose, SK2 midway to achieving it

we are constantly processing information through a wide variety of ways like when we know someone is at the door because we hear the door ring bell or we recognize a friend within our sight. Our senses are constantly at work to provide us information about our surroundings. We can think about our senses as some sort of input sensor, each one designed for a specific type of information.

The information we receive from around us has an influence on our behaviour. When a patient is attending physical therapy, the therapist is constantly interacting with him. This interaction is important in order for the patient to keep doing correctly the rehabilitation. Not only does the therapist tells him what to do but also demonstrates it and, whenever necessary,

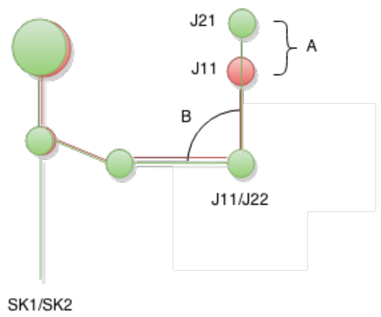


Figure 2.3: SK1 and SK2 overlapped

physically corrects him. What we observe here is the use of three different types of feedback being given to the patient - audio, visual and haptic, each one being interpreted by hearing, sight and touch respectively.

For an automated rehabilitation system to successfully work, these interactions must be simulated by other sources of feedback, in a way that the patient understands what he must do without the presence of the therapist.

Visual feedback information is often used in rehabilitation systems to communicate with a user (6). As one example of visual feedback on an AR perspective, we have the overlaying of information on an interactive mirror for the user to analyze his performance in real-time (20; 9; 26; 16; 21; 27).

Since there are multiple forms of giving feedback to a user, we can see examples where more than one are used at the same time. Combining forms of feedback can provide better understanding of the tasks to a user by minimizing the amount of information given in a visual form and, instead, distribute it. But if not designed with caution, a system can end up overloading the user with too much information at the same time.

2.4.1 Feedback Applications

A system that makes use of just one type of feedback is called a unimodal feedback system. In contrast, a system that is able to interact in more than one form of communication is considered a multimodal feedback system. The main goal of using multimodal feedback is to provide a more complete interaction with the user, since different types of feedback can complement each other and enhance the user comprehension(4).

Alhamid et al. (21) proposed a system that implemented an interface between a user and biofeedback sensors (sensors that are able to measure physiological functions). Even though it is not aimed for rehabilitation, his approach on user interaction can be analyzed. Through this interface, the user was able to access data about his body and health thanks to the measurements made by the biofeedback sensors. This system was prepared to interact with the user using multiple response interfaces, each one intended for specific purposes.

The visual interface relied on a projector that showed important messages and results from the biofeedback measurements. In the other hand, the audio interface was responsible for playing different kinds of music through speakers. The music was selected depending on the user's current state. For example, if high levels of stress are detected, calming music would be played to help the user relax.

One of the most common approaches on visual feedback is the augmented reality mirror already discussed at section 2.2. Its common use is justified by the fact that even without overlaying virtual images, it enables the user to have a spatial awareness of his own body. But since a simple reflection does not provide guidance, we could observe several examples of augmented feedback being applied to the mirror.

Tang et al. (9) explored two different designs for visual guidance on a mirror aimed at upper-limbs movement. Their first iteration consisted of virtual arrows that pointed at the targeted position for the user's hand. The second provided a trace of tubes placed along a path which represented the complete movement to be performed by the user's arm.

In both cases it was detected some difficulty in depth perception. This kind of visual cues has proven not to be suitable for exercises where the user had to move his arm towards the camera or when he had to contract it.

Anderson et al. (20) tried to provide a more detailed visual feedback by using a full virtual skeleton placed over the user reflection. In this case the goal was to mimic the skeleton's pose and hold it for a specific time. To diminish the lack of depth perception, a second tracker was placed on the user's side. Every time the system detected a large error on the z-axis, a window would appear with a side-view of both the virtual and user's skeleton for him to be corrected.

Unlike the above solution, LightGuide (1) does not rely on interactive mirrors or screens to apply its visual feedback. By using a depth-sensor camera and a light projector, they were able to project information on the user's hand. This system was able to guide the hand through a defined movement by projecting visual cues. All the information projected on the hand was being updated in real-time influenced by the current position given by the tracking device.

The visual cues varied according to the desired direction of the movement. If the current movement only required back and forward motion, only one dimension was being used. Therefore, the visual cue would only inform the user where to move his hand in the z axis through a little arrow pointing to the correct position. Two dimensional movements would combine the first visual cue by virtually painting the remaining of the hand with a color pattern. The portion of the hand closer to the desired position, would be painted with a different color than the remaining portion. They concluded that by using LightGuide, most of the users could better execute a certain movement than if they were following video instructions.

Wellner et al. (28) developed a study in which the use of sound feedback was tested in the rehabilitation of stroke and spinal cord injured patients. They stated that audio feedback should not be used exclusively but it could be used as a complement of other feedback types. The work environment involved a virtual scenario with a 3D human-shaped avatar that took a step every time the patient took one too. The virtual scenario provided a visual feedback of what was happening in the simulation. The patient was being held by an exoskeleton structure due to his inability to stand on his own, which also helped him taking steps by moving along with his legs.

One of the challenges given to the patients was to walk in a virtual corridor where small obstacles would appear in front of the avatar. In addition to seeing the obstacle, audio feedback was also provided to help the user to cross it.

The audio feedback was used to inform the patient about two factors: the distance until the next obstacle and his foot current elevation. For the distance to the obstacle, a short beep sound was produced every time interval, which was influenced by the proximity of the obstacle, similar to the idea of a sonic radar which beeps faster as an object keeps getting closer. As for the foot elevation, a continuous sound was played during the challenge, while its pitch changed according to the elevation. This allowed them to test the same challenge with and without the audio feedback, to conclude if it could influence the overall performance of a patient. Haptic feedback was also used when a patient successfully crossed an obstacle.

Even though the use of sound feedback did not significantly improved overall results, a slight confidence gain was detected on the user's performance while using it.

Focusing on the haptic feedback, Causo et al.(5) presented a paper where vibration and visual cues were used for arm posture correction. After selecting one from the six arm postures recorded, their goal was to successfully guide a patient to that same arm posture using the available feedback.

The haptic feedback could be originated from three different vibrating motors attached to the patient's arm, related to rotation on each of the three axis respectively (also known as *yaw, pitch and roll*). Each one of this actuators could be independently activated in order to correct his arm posture within a single axis.

In their experiments, a comparison was made between using solely the haptic feedback and combining it with visual cues. The results shown that using only vibration, a subject could achieve the correct posture, even though he would take much more time achieving it in comparison to the time it took when using both visual and haptic feedback at the same time. Therefore, even though haptic feedback could be used for guidance, its use could be more suitable for quick corrections and error augmentation to rapidly warn the patient of what is being wrongly done.

2.5 Related Work Overview

After analyzing several examples of feedback approaches, it is possible to make some conclusions about their usefulness, whether it be rehabilitation-oriented or not.

Below, at the Table **??**, a summary of the state of the art can be found that provides a notion of which feedback types are the most used. Each work is also categorized accordingly to specific features. These categories, which describe some key features that each work may or may not have, are as follows:

- ***Pa.*** - The **Pa**th required to execute the movement is taken into account, useful to prevent wrong executions of exercises.
- ***Ta.*** - The goal is to achieve a specific **Ta**rget. If path is not taken into account, any movement is valid as long as it reaches the target posture.

- ***R.T.*** - **R**eal **T**ime feedback is provided to keep the subject constantly informed about his performance.
- ***Gu.*** - Feedback given with the purpose of **Gu**iding the subject through a correct path. Helps the subject predict where to move.
- ***Er.*** - Feedback given is based on subject **Er**ror. Constantly corrects the subject until goal is achieved
- ***S.G.*** - Use of **S**erious **G**ames, for movement encouragement. Not completely focused on guidance.

Indeed, each of the three types of feedback observed, namely visual, audio and haptic, have shown to be more suitable for different purposes. Visual feedback appears to be normally used in regard to spatial information, due to the perception of space being the most precise when using the sense of sight. For this reason, the best option to guide a patient through movements seems to be by using visual guidance. But it is important to note that visual feedback still is a rather broad concept, therefore we could observe different takes on the whole subject of visual guidance.

The AR mirror, discussed at section 2.2.1, is the most common solution to provide visual feedback, given that it can add information to the already present mirror reflection. Even though a problem seems to persist throughout the several examples, namely the lack of depth perception. But other approaches might have a chance of solving this problem if one tries to combine them both.

The use of projection mapping,might bring some improvements to visual feedback. Based on the *LightGuide* from Sodhi et al. (1), there are reasons to be optimist about this possibility. With LightGuide, projection mapping was applied only to the hand, but their results are a good motivation to extend projection mapping to the full upper-limb and experiment with it. This technique has been normally used for entertainment and, to our knowledge, has not been fully explored in a rehabilitation context.

Unlike visual, audio and haptic feedback do not require the patient to keep his focus on the external feedback source. It allows him to concentrate on his own movement and receive feedback without looking at it, although it becomes more difficult to guide the user through more complex movements.

Audio feedback, even though being used in several of the described works, did not have such an important role as the visual feedback. Despite not normally being the main source of a patient's guidance, there is significant evidence that a rehabilitation system can benefit from using audio for some of its needs. Sound does not only help with the immersion in a rehabilitation environment but it is also useful to alert the patient about specific events. It can provide the patient with a better control of his timing when necessary, for instance to inform him of the right moment to evade an obstacle (28). This application of audio feedback is backed up by the fact that the sense of hearing provides a great perception of temporal information (4).

Observing the Table **??**, we can see that haptic feedback was the least used of the three. Perhaps due to requiring more specialized equipment to apply more detailed feedback, unlike audio which requires only a set of speakers and visual which can be achieved just as easily. Even so, haptic feedback could be useful to emphasize certain aspects, such as error augmentation (5) which may promote motor learning due to enabling a patient to be more aware of his mistakes(4). For haptic feedback to be used for guidance purposes, it would be necessary to have equipment capable of applying physical force on the patient, but since visual feedback has already proven to be an adequate provider of spatial information, we can place haptic feedback in a secondary position.

3 SleeveAR

Summary

4 Architecture

{TODO: INCLUIR ISTO NA IMPLEMENTACAO}

Summary

In this section, we will present our proposal which will be divided as follows. In the first place, in section 4.0.1 we explain our goals in detail and what we consider to be an innovation. Next, section 4.0.2 will present the planned architecture with a step-by-step explanation for the reader to fully understand the desired work flow. The final section will list the tools that we plan to use in the implementation of our approach.

4.0.1 Main Objectives

Hereby, we present our proposal in which we aim to further explore the possibilities of multimodal feedback applied in a rehabilitation context.

We plan to combine multiple sources of feedback: visual, audio and haptic feedback, in order to evaluate how the patient responds to these sources of guidance throughout the execution of a given movement.

To provide a dynamic feedback that constantly reacts to the patient's movements, we will rely on real-time skeleton tracking through a motion capture device.

The use of projection mapping in a rehabilitation environment has not been experimented yet, and we have reasons to believe it can bring great benefits to the methods of guidance applied to a patient in this kind of rehabilitation systems. If combined with an augmented reality mirror and audio or haptic feedback, we will be able to approach the same exercises in different ways in order to evaluate which feedback combinations can make the patient understand more clearly the required movements.

To control these feedback sources, a rehabilitation system will be implemented.The system will be capable of manipulating the feedback in order to guide the patient through a predefined exercise which must be previously learned by the system through demonstration. This way, the system is only responsible for guiding the patient to a correct execution of the chosen exercise.

We will focus this initial proposal only on exercises related to upper limb movement to simplify the implementation and reduce the number of factors that would need to be taken into account. This way we can experiment more with multimodal feedback and achieve more precise results.

4.0.2 Architecture

The planned architecture of our proposal is divided into two different parts. The first, called *Learning Architecture*, consists of the process for obtaining an exercise model by demonstration for further use. The second and most important part, called *Teaching Architecture*, concerns the application of the multimodal feedback for another person to recreate the exercise model.

4.0.2.1 Learning Architecture

The first part of our architecture serves the purpose of generating an exercise model which will be used for teaching and guiding exercises' execution.

As we can see in Fig. 4.1, we start by having a PT demonstrating the prescribed exercise (1). Through motion capture devices, the PT body is tracked during the demonstration and the tracking data is stored in a storage infrastructure.

Then, all the tracking data recorded is sent to the *Exercise Generator Module* (2) in which the data will be sanitized (e.g., remove tracking data whenever the PT is not performing the exercise) to be fed into the next step.

Finally, the resulting data will be returned from the *Exercise Generator Module* to an element denoted *Exercise Model* (3), which will consist of modelling all the useful data required to recreate the exercise initially demonstrated by the therapist.

The generated *Exercise Model* will be the foundation of our Architecture's second part, described hereafter.

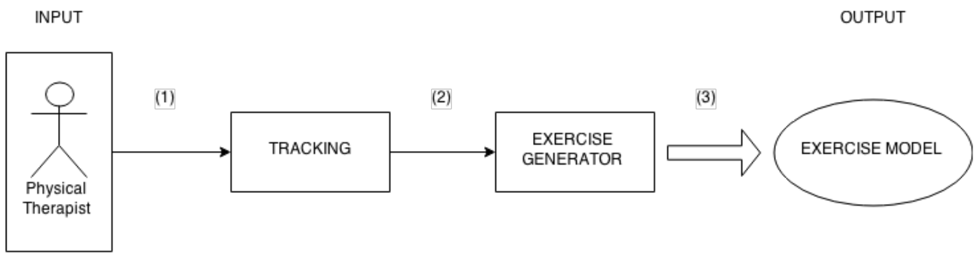


Figure 4.1: Learning Architecture Diagram

4.0.2.2 Teaching Architecture

The second part of our architecture serves the purpose of taking advantage of multiple feedback interfaces in order to guide a patient through the execution of a previously recorded exercise, the already described *Exercise Model*.

As shown in Fig. 4.2, it starts by loading the desired exercise that was generated in the *Learning Architecture* (4), which will be the basis for comparison with the patient's body.

In this case, the tracking module is responsible for constantly sending the tracking data to the *Multimodal Feedback Manager Module*(MFM) (5,6).

The Multimodal Feedback Manager (MFM) module holds the core of our approach. While receiving real-time tracking data from the patient, the module will compare his current posture to the *Exercise Model*. With this in mind, the module will communicate (7) with the available feedback interfaces in order to guide the patient, for him to achieve a similar movement to the one recorded. The module will manipulate each interface independently from one another, to easily create different combinations of feedback so that we can evaluate their validity. Each one of the three feedback modules available will consist of devices capable of interacting in the desired feedback type: visual, audio or haptic.

While the patient is still executing the exercise, the required feedback will continue to be applied (8, 9, 10). Therefore, as the patient keeps changing his posture, the tracking data will also be updated and therefore, affecting the resulted feedback. This process (5-10) will remain in cycle until the given exercise is finished.

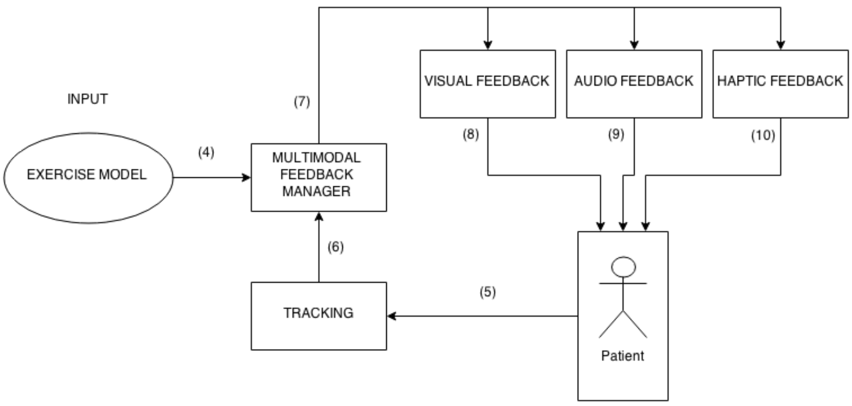


Figure 4.2: Teaching Architecture Diagram

5 Implementation

Summary

This section will describe the necessary steps taken for our SleeveAR's implementation. First of all, section 5.1 will briefly explain the overall architecture which served as a guiding tool for our implementation. Second, at section 5.2 we will dig deeper into the the most important aspects that made possible to develop the tool here presented.

5.1 Architecture

5.2 Development

5.2.1 Tracking Devices

For the proposed approach to work, it is necessary to track the subjects as accurately as possible. There are more than one available alternatives that can be used as the tracking device.

The first makes use of the recently released, Microsoft Kinect One[1] (previously baptized as Kinect 2), which supposedly offers a better tracking quality than the previous version, Kinect 1. Although this might be true, to the best of our knowledge there are still no published studies which use the new Kinect in order for us to understand if this would be the best choice for our approach.

The other alternative available at our laboratories is an OptiTrack Motion Capture system [2]. This option could offer us a more precise tracking and the possibility of dealing with occlusions due to the multiple cameras scattered around the room. The downside is the fact that it requires

[1] http://www.xbox.com/xboxone/kinect
[2] https://www.naturalpoint.com/optitrack/

body markers to be used in order to successfully detect a person, unlike the Kinect which detects the human body through software algorithms.

Occlusion problems are much more likely to occur using Kinect than with the OptiTrack, due to only using one motion capture sensor. There can be moments where the patient could point his arms forward making the Kinect lose sight of the rest of the body. These problems were known to happen with the first Kinect, for the newest version we will need to understand if it still happens.

We intend to develop a comparison test between the tracking devices available. With this test we will be able to evaluate the tracking quality of each device and therefore decide which one would be the more suitable for our implementation.

5.2.2 Feedback Devices

To be able to provide guiding cues to a patient, we will need a group of devices capable of providing each of the three possible feedback types that were presented.

For the visual feedback, we will rely on two concepts: the AR mirror and projection mapping. For the first, we will capture the patient's image with a camera and project it into a screen. This way it is simulated a mirror, similar to other approaches discussed in this work. As for the projection mapping, a light-projector will be used in order to, combining with the the tracking device, project visual cues on the patient's body.

To provide audio feedback, a set of speakers will be required around the patient. Therefore, enabling the reproduction of surround sound to explore possible sound localization experiments.

Finally, the haptic feedback will rely on vibration applied onto the user by using vibratory actuators attached to his arm. One possible option would be using the *Pebble Smart watch*[3] that provides a Developer Kit to access its features, which includes vibration motors. By implementing a communication channel with the watch, it will be possible to control its vibrations whenever necessary.

[3] `https://getpebble.com/`

5.2.3 Software Tools

To implement our software responsible for interacting with the several feedback interfaces that will be used, we will choose the *Unity3D* game engine[4]. This engine already provides several tools that facilitate the development of augmented reality applications and we have in our possession already developed frameworks to communicate with the available tracking devices.

The Kinect Tracking Device already provides an SDK for Unity applications which, if Kinect ends up the chosen tracking device, will accelerate the implementation of the Tracking Module described in section 4.0.2.

As for the Pebble Smart watch, although there is an SDK available, it does not support Windows at the moment. If the Windows SDK is not released in the next weeks, we will use the other alternatives provided by the Pebble team which will consist on using an Android phone as a bridge between the Pebble and our application.

[4] `http://www.unity3d.com`

6 Evaluation

Summary

For the evaluation of the SleeveAR, we intended to observe how well could a subject recreate simple arm movements by only following the feedback at his disposal. In this section we will present a detailed description of the type of tests that were made, what type of information was being gathered and also highlight some of the most important critics received by a professional physical therapist after using our system.

Since the test would involve executing simple arm movements, five different exercises were created for this evaluation. {TODO: colocar links de youtube?} These exercises were recorded both by video and by the SleeveAR's Learning Architecture at the same time. This way, we knew for certain that it was the same movement being stored in video and in our system.

In this chapter we present the methodology used for testing our prototype with test subjects. All the results will be discussed in order to achieve a better understanding about our prototype success. In the end a meeting with a physical therapist, from which resulted a great discussion and exchange of ideas, will also be fully reported.

#	Stage	Time
1	Introduction	2 minutes
2	SleeveAr	15 minutes
3	Video	10 minutes
4	Questionnaire	3 minutes

Table 6.1: SleeveAR evaluation stages

6.1 Methodology

In this section we describe what methodologies were used to test our prototype. Each of our participants followed this methods similarly.

The average time spent with each participant was approximately thirty minutes. The test was composed of four stages as we can observe in Table 6.1.

1. **Introduction**

   Before the actual test, a brief explanation was given about the main goal of our thesis. The participants were also made aware of what would the full experimental test consist of.

2. **SleeveAR**

   The participant would have to execute exercises, described in section 6.2, while following our prototype real-time feedback.

3. **Video**

   For each of the five exercises selected for this evaluation, the participant would have to watch a video of its execution at least two times. Then, while following the video playing, the participant would execute the same movement based on what he was observing.

4. **Questionnaire**

   Finally, a small questionnaire would be filled by the participant. This questionnaire included questions about stage 2 and 3 while also providing us some information about the user's profile.

In order to gather data for further result analysis, each execution of an exercise generated a Log with all the necessary information about the participant's movement. {TODO: descrever Logs mais detalhadamente}

Even though we are ordering the stages this way, half of the participantes started by doing the third stage before the second, for the purpose of obtaining a more balanced sample of results.

6.2 Performed Tasks

For both the second and third stage described in the previous section, the same five exercises were executed.

Each exercise was simultaneously recorded witg a video camera and with motion tracking devices. Under these circunstances, we made sure that the content being stored in video format directly represented the data being stored on SleeveAR's architecture. The tasks performed in stage 2 and 3 had the same goal of recreating the five exercises recorded.

{TODO: explicar como era cada exercicio?}

6.3 Environment and Participants

6.4 Results

The empirical evaluation addressed the correctness of the executed exercises. Experiments with test subjects were performed for a baseline scenario, consisting of exercise execution through video observation, and for the proposed prototype. The performance metrics is given by the degree of similarity between the participants' arm trajectories and the original trajectories demonstrated by the therapist. It is measured using the **Dynamic Time Warping (DTW)** {TODO: referencia para o algoritmo} algorithm, which is appropriate for measuring a degree of similarity between two temporal sequences which may vary in time or speed. With the application of this algorithm in mind, the recorded movements can be reformulated as a sequence of positions. One can then compare the performance values for both the proposed solution and the baseline scenario.

Due to an arm movement being divided by the upper and fore arm sections, the DTW was applied to each individually, thus providing us with a more detailed set of values. By doing said division, we could observe if there were notable performance differences between each arm region.

The final DTW values of each exercise are the result of adding both arm regions' DTW values. It is important to highlight that with the following results, DTW values closer to zero directly represent movements more similar to the original.

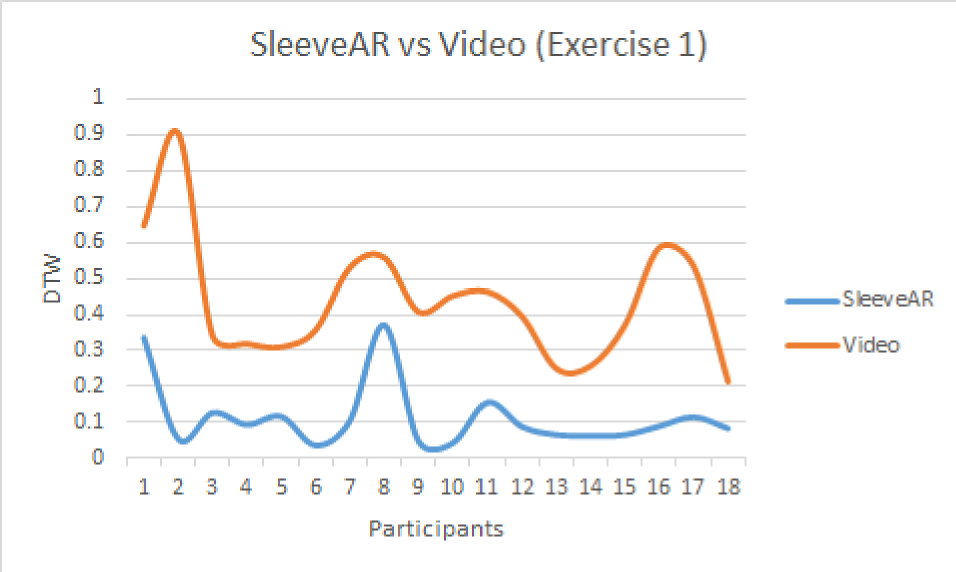


Figure 6.1: Exercise 1 DTW comparison between SleeveAR and observing video.

	Exercises				
	1	2	3	4	5
SleeveAR Average DTW	0.1142	0.1472	0.3262	0.1289	0.3801
Std Dev	0.0903	0.148	0.2005	0.0595	0.2762
Video Observation DTW Average	0.439	0.263	0.3549	0.1945	0.2733
Std Dev	0.1647	0.0921	0.1697	0.0657	0.0887

Table 6.2: My caption

For the first exercise, we can observe in Figure 6.1 the test results from all participants, both using the SleeveAr and by observing the respective video.

These results clearly show SleeveAR provided a higher similarity when comparing to the original exercise. In terms of statistic values, participantes achieved an average DTW value of **0.114181315** and a Standard Deviation of **0.090349091** when using SleeveAR. On the other hand, an average DTW value of **0.438959688** and a standard deviation of **0.164684962** was achieved when relying on video observation. Based on these results, in the first exercise, SleeveAR clearly improve participant's performance which were able to re-create the original exercise better then by video observation.

Table 6.2 presents the average DTW and standard deviation for all five exercises {TODO: aqui mudar para grafico em vez de tabela}

Focusing only on SleeveAR results, figure 6.2 presents the average DTW on each of the three tries a participant had for each exercise. These results clearly show an improvement on

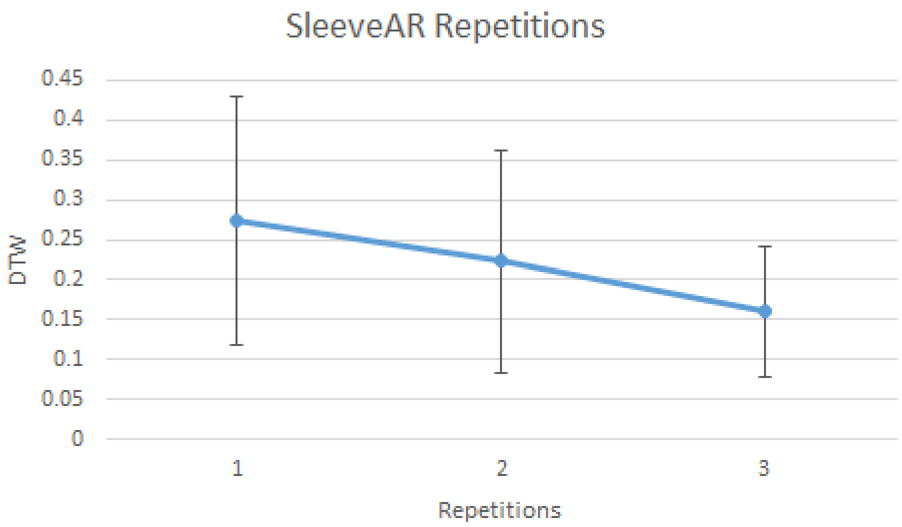


Figure 6.2: Exercise 1 DTW comparison between SleeveAR and observing video.

a patient's performance in just a small number of repetitions. Not only the average DTW values become lower, meaning closer to the original, but also the standard deviation appears to diminish.

Since with each repetition, the participant is able to see where he failed the most {TODO: falar na implementation sobre a session review}, it allows for a improvement on his next repetition.

6.5 Validation with Physical Therapist

We had the opportunity of meeting with a professional physical therapist which accepted our invitation to test the SleeveAR prototype and provide us with some feedback in a small interview.

Prior to the interview, it as decided that the therapist would be part of the same tests being done for our evaluation, which have already been described in this chapter {TODO: ref}. Under those circumstances we were able to demonstrate the full potential of our prototype and, as a result of these tests, we received some very interesting feedback.

First of all, this prototype main vision was to prove we were able to guide subjects through pre-recorded exercises in order for them to be as close as possible of the original exercise. With this in mind, we wanted to know in what way would this kind of tool be useful in a regular physical therapy work environment. We also wanted to understand what would be missing to make SleeveAR a more complete tool for a common use along this field of rehabilitation.

We will now present the most notable feedback received, both positive and negative.

- **Missing feedback from one of the three axis**

  For SleeveAR feedback to be fully complete, it would need to take into account the missing axis of movement in its real-time feedback. Since this prototype focused on guiding the arm through relatively simple movements, we did not detect this problem. But, consequently, in the evaluation tests, we realized that it might have helped to take this into account. In Fig **fazer figura** we can see an example where, without verifying the upper arm's rotation, our system considers both arm poses to be the same. This happens because both the upper arm direction and angle between the upper and fore arm remain the same.

- **Arm obstructs visibility**

  Ocasionally, the right arm might obstruct the user's vision, making it difficult to observe the feedback being projected onto the floor. This issue could be solved by projecting all the visual feedback further away from the subject

- **Increase number of tracking points in shoulder area**

  In physical therapy, a lot of arm movements also focus on the shoulder area. With this in mind, it would be necessary for our sleeve to contain more tracking points around the shoulder instead of only having a tracking point for the shoulder, elbow and wrist.

- **Potential useful tool for patient reports**

  Some physical therapists follow a group of standard arm movements to initially evaluate a patient's condition. With this tool, they could receive full reports with necessary data that otherwise they would have to measure physically. It could be possible to extend SleeveAR to return several additional information about a patient's range of movement after executing a group of exercises. This would allow a physical therapist to have access to information much faster and, possibly, more precise about the patient.

  Also, with the possibility of recording movements and later replaying them, SleeveAR could offer a great way of demonstrating the patient, in a visual form, how much he has improved over the course of his rehabilitation, by replaying the recordings of his movements.

- **A great tool to help a physical therapist when multi-tasking**

  While working in a physical therapy gymnasium, therapists often have to look after several patients at the same time. Tools like SleeveAR could help the therapist by lowering the amount of times they have to correct a patient and, therefore, focus on another patient that might need more priority help.

- **Provides a great motivation with the feedback received**

  The KP and KR demonstrated in SleeveAR is very satisfactory and could really help in motivating a patient while showing his evolution as he keeps repeating the exercises.

  Being able to show how the patient performed by drawing his trajectory over the original exercises helps understanding which parts need improvement. Also, the real-time feedback does a great job at instantaneously showing the patient what to correct on his exercise.

6.6 Discussion

results x therapist

7 Conclusions

Summary

7.1 Conclusions

Using augmented reality with multimodal feedback for rehabilitation allows a patient to have a source of guidance and correction when executing exercises outside of a clinic. This would be preferred, as opposed to exercising with no feedback where there is no way of correcting the execution.

The state of the art presents several solutions to provide guidance during movement's execution, some already applying multimodal feedback. Even so, several problems with the patient's perception of the feedback have been reported, and clearly there is still room for improvement when combining sources of feedback.

With our proposal, we will be able to evaluate which feedback combinations could be more suitable for guiding a patient while solving some of the perception problems and also contribute with different feedback techniques in addition to the ones observed in the state of the art.

7.2 Future Work

As future work we would like bla bla.

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